National Aeronautics and Space Administration

Investigation of Adaptively Controlled, Variable Geometry Deceleration Systems

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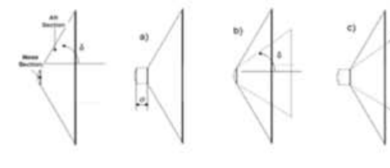
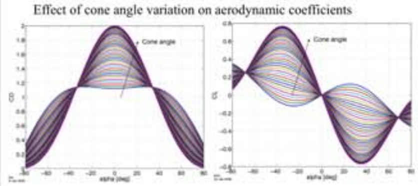
Project Objective:

The objective of this study was to investigate novel structural and control concepts for planetary entry trajectory modulation using variable geometry decelerators. Entry trajectory can be significantly improved to reduce entry range errors and alleviate deceleration peaks if the hypersonic aerodynamic performance of the decelerator is tunable during flight.

We have considered a vehicle with an afterbody that is expanded to increase drag at high altitudes and high speeds, and that can be contracted at lower altitudes and speeds to decrease drag. For maneuvering entry vehicles with blunt sphere-cone geometry, one common approach is to trim the vehicle at a nonzero angle of attack to produce lift by center-of-gravity offset through most of the hypersonic entry phase. However, the vehicle needs to turn to a lower angle of attack prior to supersonic parachute deployment. Currently, MSL relies on expelling ballast masses of 100 kg in making a pitch maneuver to reduce the angle of attack. Such maneuvers cannot be repeated during flight without added mass penalties. An alternative approach to the aerodynamic control problem is to embed a variable geometry decelerator in the design of the vehicle.



Effect of cone angle variation on aerodynamic coefficients



Example of Guidance Law for Constant Drag Tracking

Error

$$e_D = D - D_{ref} \longrightarrow \ddot{e}_D + 2\zeta_D\omega_D\dot{e}_D + \omega_D^2 e_D = 0 \quad \text{Error dynamics}$$

$$\ddot{D} + 2\zeta_D\omega_D\dot{D} + \omega_D^2\left(D - D_{ref}\right) = 0$$

$$\dot{D} = -2c_1\rho V\frac{D}{m} - 2c_1\rho Vg\sin\gamma - c_1\beta_a\rho V^3\sin\gamma$$

$$\ddot{D} = -a_1\dot{\gamma} - b_1$$

$$a_1 = c_1\rho V\cos\gamma(2g + \beta_a V^2)$$

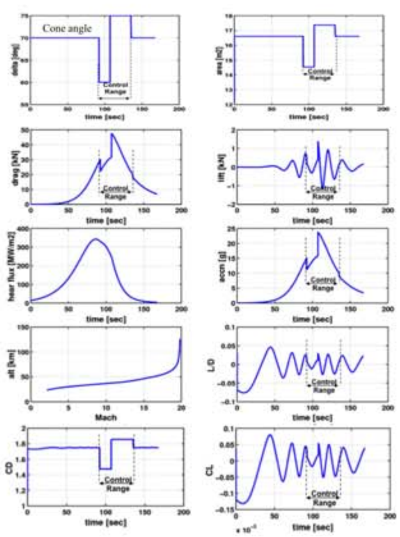
$$b_1 = 2c_1\left(\dot{\rho}V\frac{D}{m} + \rho\dot{V}\frac{D}{m} + \rho V\frac{\dot{D}}{m}\right) + 2c_1 g\sin\gamma\left(\dot{\rho}V + \rho\dot{V}\right) + c_1V^2\beta_a\sin\gamma\left(\dot{\rho}V + 3\rho\dot{V}\right)$$

Commanded flight-path-angle

$$\dot{\gamma}_{Cmd} = \frac{2\zeta_D\omega_D\dot{D} + \omega_D^2\left(D - D_{ref}\right) - b_1}{a_1}$$

Commanded bank angle

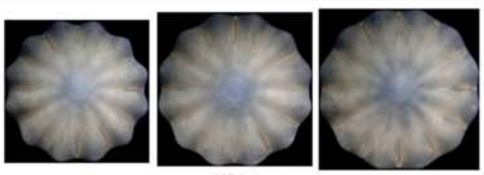
$$\sigma_{Cmd} = \cos^{-1}\left[\frac{V\dot{\gamma}_{Cmd} + \left(g - \frac{V^2}{r}\right)\cos\gamma}{L/m}\right]$$



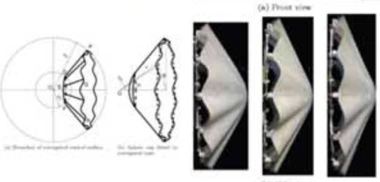
Benefits to NASA and JPL (or significance of results):

Changing the aerodynamic characteristics of a flight vehicle by active means can potentially provide a mechanically simple, affordable, and enabling solution for entry, descent, and landing across a wide range of mission types, including ballutes and aerobots (blimps, balloons), sample capture and return, and reentry to Earth, Titan, Venus, or Mars. Unguided ballistic entry is not sufficient to meet this more stringent deceleration, heating and targeting demands. Active guidance is needed and this requires more general aerodynamic control capabilities in the entry vehicles. All future planetary missions involving a reentering vehicle designed to glide, steer, and precisely land a reentering vehicle on a planetary surface will benefit from our findings.

Until now, variable geometry aerodynamic systems that have been considered for planetary applications are primarily of the inflatable type; all are at low TRLs. Our proposed concept of a decelerator system that is first deployed and then is able to adaptively change its geometry during operation is novel and is expected to lead to reductions of drag up to 20% and peak temperature by 20%, thus obviating the need for both expensive thermal protection systems and heavy expelled mass ballast to change the aerodynamic configuration of the vehicle.



(a) Front view



(b) Side view

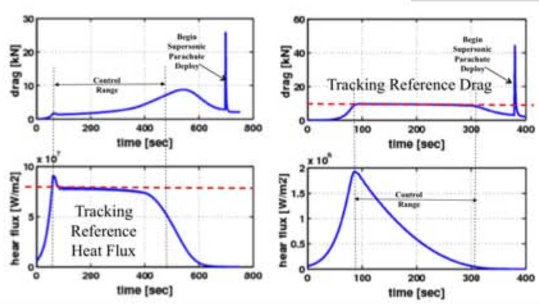
Table I. Corrugated shell model parameters

Diameter (m)	4.50
Bluntness Ratio	0.17
Nose Radius (m)	0.985
Number of Corrugations	12
Corrugation Amplitude (mm)	112.5
Shell Thickness (mm)	3.0

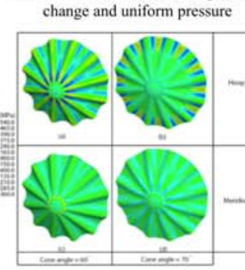
Figure 11. Geometry variation of corrugated shell model.

Publications:

- Marco Quadrelli, Dhemetrio Boussalis, Greg Davis, Sergio Pellegrino, Kawai Kwok: *Structural and Control Concepts for Variable Geometry Planetary Entry Systems*, presented at the 17th AIAA/ASME/AHS Adaptive Structures Conference, 4 - 7 May 2009, Palm Springs Convention Center, Wyndham Palm Springs. Palm Springs, California.
- Marco Quadrelli, Sergio Pellegrino, Kawai Kwok: *Structural and Trajectory Control of Variable Geometry Planetary Entry Systems*, presented at the AIAA SPACE 2009 Conference and Exposition, Pasadena, California, 14-17 September 2009.
- NTR # 47102.



Distribution of stresses due to geometry change and uniform pressure



Geometry of segmented shell

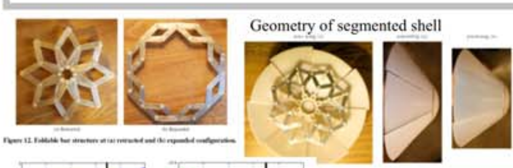


Figure 12. Foldable bar structure at (a) retracted and (b) expanded configuration.

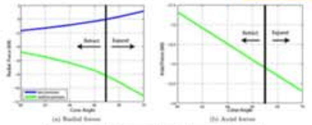


Figure 15. Reaction forces for cone angle variation in corrugated shell model.

FY09 Results:

The results from this investigation apply to a generic vehicle entering a planetary atmosphere which makes use of a variable geometry change to modulate the heat, drag, and acceleration loads.

Innovative structural concepts are presented that are very promising to implement a variable geometry aerodynamic shape. A structural analysis of these proposed structural configuration shows that the stress levels are tolerable during entry. Two structural concepts for implementing the cone angle variation, namely a segmented shell and a corrugated shell, have been presented. Scaled prototypes for both concepts were fabricated.

They have demonstrated that continuous variation in cone angle is achievable.

Guidance laws that track reference heat flux, drag, and aerodynamic acceleration loads in the longitudinal plane are also proposed and show good performance. These guidance laws, based on dynamic inversion, have been tested in an integrated simulation environment, and the results indicate that use of the guidance laws and of variable geometry are feasible to track specific profiles of dynamic load conditions during entry.

Further work will also include tuning the current corrugated shell geometry using an energy-based optimization approach to minimize stress and actuation force, wind tunnel measurements on small scale prototypes during geometry change, exploring trajectory modulation with decelerators undergoing asymmetric variation in geometry, and the control allocation of the mechanical effort for combined attitude and trajectory control.

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